Nuclear Theory - Course 127

THE APPROACH TO CRITICAL AND THE RAISING OF POWER

There are two stages involved in bringing a reactor up to power and these are:

(a) The approach to critical during which the value of k is increased until the reactor becomes critical.

(b) Increasing the power until the operating level is reached.

The reactor is in its most dangerous condition when it is shut down, for several reasons:

(a) Unexpected increases in reactivity and therefore in power are more likely since it is possible that the regulating and protective system may be "off scale". Under these conditions a fault in either system is not as easy to detect.

(b) Much larger power increases are possible, as a result of reactivity increases, at low power level than at high power levels.

(c) With the heat transport system depressurized, a power surge could result in boiling of the heat transport fluid, which could further increase the reactivity (as will be seen in the next lesson).

(d) The response of the instrumentation is slower compared with the possible reactor periods.

The approach to critical is, therefore, a procedure that must be undertaken with a great deal of respect and it will be considered at some length in this lesson.

Subcritical Operation

During the approach to critical the reactor is subcritical and so, before considering the approach itself, it would be desirable to have considered the manner in which a reactor behaves when it is subcritical and k is less than 1.

It was shown, in a previous lesson, that if a source of neutrons, of strength P_s watts, exists in the reactor, then, on shutdown, the reactor power will decrease to a value given by:

$$P = \frac{-P_s}{\delta k}$$

where δk is the amount of negative reactivity introduced when the reactor is shut down.

Now the reactivity is a measure of how far the reactor is from being critical and $\delta k = k - 1$ or $-(1 - k)$.

$$\text{Therefore} \quad P = \frac{P_s}{-(1-k)} = \frac{P_s}{1-k} = \frac{1000\ P_s}{\text{milli-k below critical}}$$

If P/P_s is plotted against time for various values of k, a series of curves, as shown in Fig. 1, are obtained. Of what significance are these curves?

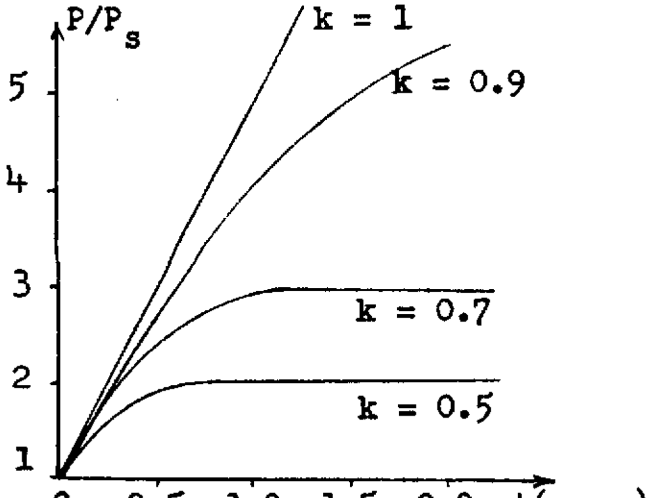

Fig. 1

Supposing that the value of k was initially negligible. If now the moderator level was raised until k = 0.5, the reactor power will increase as shown in the lower curve and level off at 2 P_s in half a second or so.

As k is increased, the power levels off more slowly but at a higher value, until, when k = 1 the power continues to increase without levelling off at all.

Now, if P_s is very small, as it is when spontaneous fissions only supply the neutron source, the power at which the reactor levels out is very small until k is close to 1.

Suppose P_s = 0.0001 watts with spontaneous fissions.

$$\text{When } k = 0.1 \quad P = \frac{P_s}{0.9} = \frac{0.0001}{0.9} = 0.00011 \text{ watts}$$

which would be too low to get much of a reading even on sensitive fission count rate meters.

$$\text{With } k = 0.5 \quad P = \frac{0.0001}{0.5} = 0.0002 \text{ watts}$$

Therefore k would have to be close to 1 and the reactor close to being critical before even count rate instruments were effective. In addition the neutron multiplication is subject to wide statistical fluctuations. Since it is necessary, at each value of k, for the power to level off as in the curves in Fig. 1, to determine whether or not criticality has been achieved, the critical point may well be passed while the neutron power is still low. By the time the power has risen to the point where it becomes obvious that it is increasing, the rate of rise may be so rapid that the reactor cannot be shut down fast enough to prevent damage.

To avoid this possibility a neutron source is placed in the reactor so as to artificially increase P_s and provide a good count rate. When k is large enough for a good count rate, with spontaneous fission sources alone, the neutron source is removed.

With photoneutron sources, on the other hand, P_s may be 30 watts.

Thus when k is only 0.1 or 900 mk below critical $P = \frac{30}{0.9}$

$= 33.3$ watts.

This value is only about 7 decades below full power and within the range of the most sensitive linear neutron instruments which normally go down 8 decades. Since this source term is so much greater than that due to spontaneous fission, special fission chambers and count rate meters would not be required.

The First Approach to Critical

In the CANDU type of reactor, the approach to critical is likely to be made by raising the moderator level until enough fuel is covered to sustain a chain reaction. If absorber rods are also available for reactivity adjustment, they would be completely withdrawn. If variation in moderator level is not possible and reactivity control is by absorber rods only, then the approach to critical would have to be made by gradual withdrawal of the absorber rod. However, it will be assumed that the former method is to be used, as in fact it was at NPD and will be at Douglas Point.

The initial critical level, with fresh fuel, will be much lower than the normal operating level. Some attempt is usually made to raise this initial critical level such as by replacing some of the normal natural uranium or uranium oxide fuel with depleted fuel (ie, having less U-235 content than natural uranium). However, even with depleted fuel the initial critical level in NPD was 97.5" compared with the normal operating level of about 160". The estimated initial critical level in Douglas Point is only 36% of full calandria and this would not cover the depleted fuel region. Also a 1" change in level in this region is equivalent to a 2.5 mk reactivity change. Boron addition to the moderator is being considered which would raise the initial critical level to 50% of full calandria. However, this involves the control of an additional parameter at a time when this is least desirable.

The first approach to critical is considered more hazardous than subsequent approaches because:

(a) There are only spontaneous fission sources and no photoneutron sources, in the core and therefore the normal neutron power instruments are not nearly sensitive enough to measure the neutron density.

(b) The neutron power instruments have not, in any case, been calibrated and, therefore, cannot be relied on.

(c) The automatic regulating system is inoperative.

(d) The critical height of the moderator is not known, ie, it is not known at what moderator level the reactor will go critical.

(e) Large reactivity increases are possible because the xenon and other fission product poison are absent.

The first approach to critical is, therefore, carried out in such a manner that recognition is given and allowances made for the problems that do exist. Because the regular neutron power instruments cannot be used, sensitive neutron fission chambers or BF_3 counters are used during the approach. These fission chambers or counters are normally lowered into the core so that they are in a higher flux region. They are connected to count rate meters, because the actual power level is so low, so that the neutron count rate is measured rather than power. Three such detectors are normally used so that three independent count rates are established. This allows for error or failure of one counter and also allows for greater flexibility when the neutron density increases. A neutron source is placed in the core so that a reasonable count rate is obtained at values of k well below critical. This avoids statistical errors on the counters.

If the detector used is sensitive enough to be used with spontaneous fission sources only, a neutron source would still be used to check the operation of the detectors.

The moderator level is raised in small steps (1 or 2 inches at a time) and the neutron power allowed time to level out as shown on the curves in Fig. 1. For small values of k the count rate levels out rapidly but, as k increases, it takes progressively longer to level out. As k increases the count rate increases and eventually the fission source can be removed. Also the fission chambers have to be moved further out from the core to prevent them saturating. The critical moderator level is predicted by plotting the reciprocal of the count rate against the reciprocal of buckling, $1/B^2$, on the three independent counters. For a cylinder:

$$B^2 = \frac{(2.405)^2}{R^2} + \frac{\pi^2}{H^2}$$

Therefore, for a vertical cylindrical reactor, where R remains constant and only H changes, the reciprocal of the count rate is plotted against H^2.

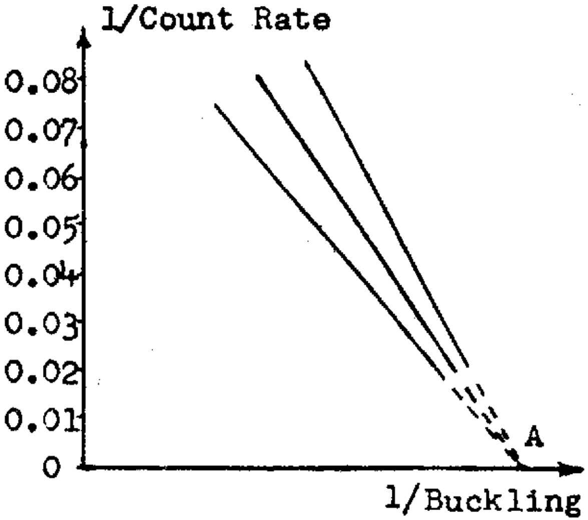

Fig. 2

For a cylindrical reactor, with its axis horizontal, the portion of the core covered by moderator, is only a portion of the cylinder. Therefore, the buckling is a more complex expression than that shown above. A curve, relating buckling to the distance L of the moderator level below and above the reactor centre line, is shown in Fig. 3. The reciprocal of the count rate is plotted against the value of $1/B^2$ for each value of moderator height.

The three straight lines shown in Fig. 2 are then obtained, which converge on the point A when the count rate is very large or the reactor is critical. The point A, then, gives the value of $1/B^2$ when the reactor will be critical and this can be converted back into the critical moderator height.

Because of the difficulty of estimating accurate values for the buckling for a horizontal cylinder, an alternative approach is sometimes used. As was shown previously, the multiplication factor of source neutrons in a subcritical reactor is $1/(1-k)$. Thus the neutron count resulting from the neutron source is enhanced by a factor of $1/(1-k)$.

$$\text{ie,}\quad \text{Count Rate} = P_s \times \frac{1}{(1-k)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Therefore a graph of the reciprocal of the count rate against $(1-k)$ should be a straight line and so should the graph of reciprocal count rate against k. The multiplication factor k can be calculated as a function of the moderator level. When the reciprocal count rate is plotted against k, three straight lines are obtained as in Fig. 2 and the point A again extrapolated. The value of k at A is then converted back into the critical moderator height. This approach was adopted at NPD and is likely

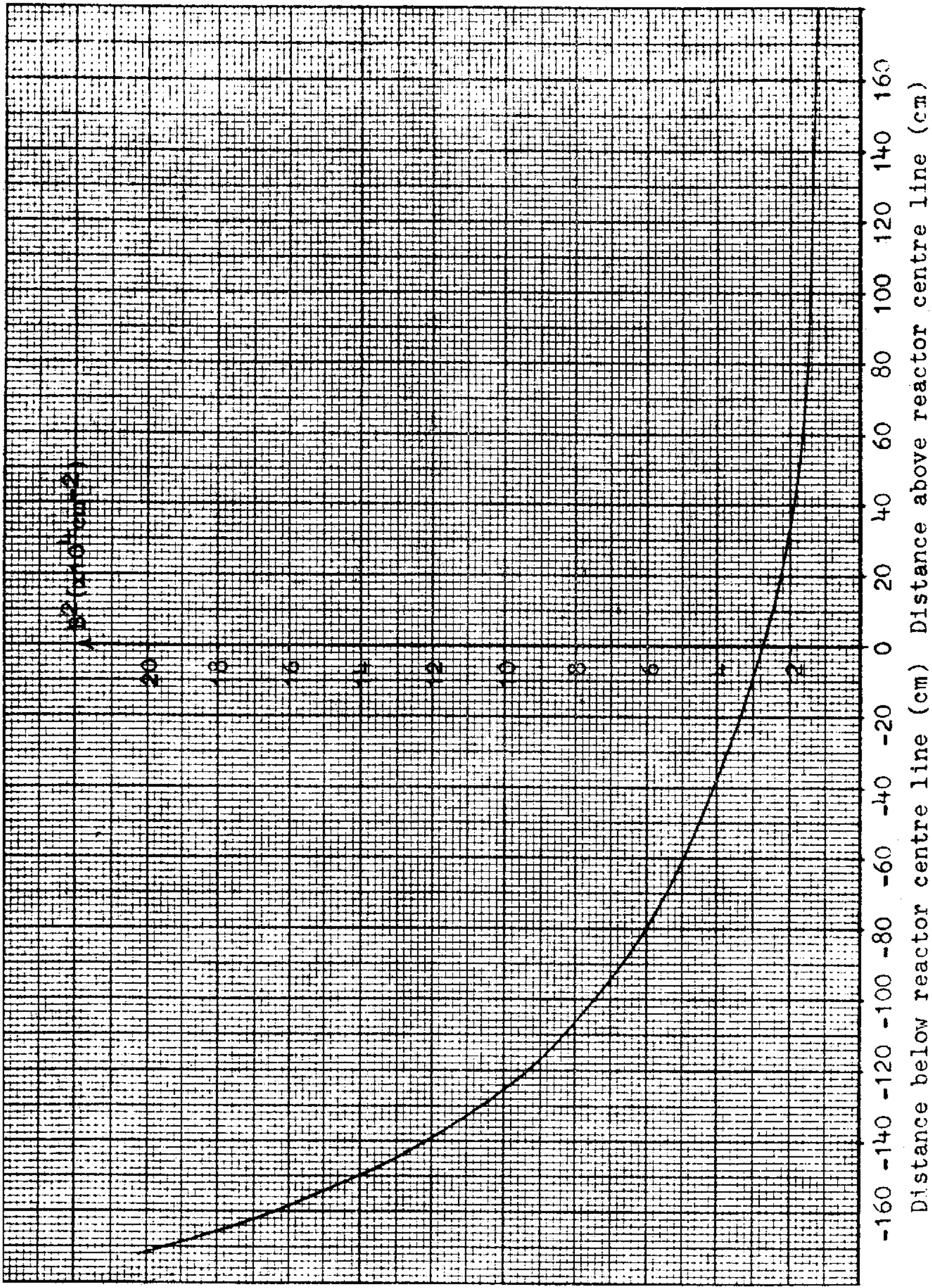
B² (×10⁻⁴ cm⁻²)
20
18
16
14
12
10
8
6
4
2
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
Distance below reactor centre line (cm)
Distance above reactor centre line (cm)

Fig. 3

to be the method used at Douglas Point. Fig. 4 shows a typical plot on one of the fission chambers during the NPD first approach to critical. Slight deviations from the straight line can be observed as the moderator level passes the various rows of fuel.

When the critical height has been established, as accurately as possible, it is approached cautiously until the power starts to increase on a long period, which shows that the critical moderator level has just been exceeded. For instance, in NPD when the moderator level was within 1.5 inches of the projected critical height, the level was raised through critical and the reactor power allowed to increase on a 150-second period. At 10^4 counts per second the level was adjusted to hold the count rate steady. This adjusted level is then the initial critical level. Note that prior to this last step being taken, one detector is moved away from the maximum flux region to ensure that one chamber continues to read in the range in which it had been checked and calibrated.

The same approach to critical, as has just been described, would have to be used if the reactor is shut down for longer than four months or so. The fission products would then have decayed to such an extent that the photoneutron sources are too small to be of value.

In a graphite or light water moderated reactor every approach to critical is the same as the initial approach since no photoneutron sources are built up.

Subsequent Approaches to Critical

In a heavy water moderated reactor, fission products accumulate in the fuel if the reactor has been operated at power. So, for subsequent startups, the photoneutron source in the reactor will be large enough to give a reading on the lower range of the most sensitive neutron power instrument. Therefore, no special neutron counters or neutron sources are required. However, the neutron power signal is too weak for satisfactory automatic operation of the regulating system, unless the shutdown was of short duration. The approach to critical is, therefore, made on manual control using the normal neutron power instruments.

The moderator level is allowed to rise in steps of 1" or so at a time. After each 1" step the moderator level is held constant until the subcritical power reaches an equilibrium value. When the power continues to increase the critical level has been exceeded. The level is then adjusted down until the power is held constant. An estimate of the critical level can be made by plotting the reciprocal of neutron power against the moderator height. The point where the graph crosses the moderator height axis will indicate the possible critical level.

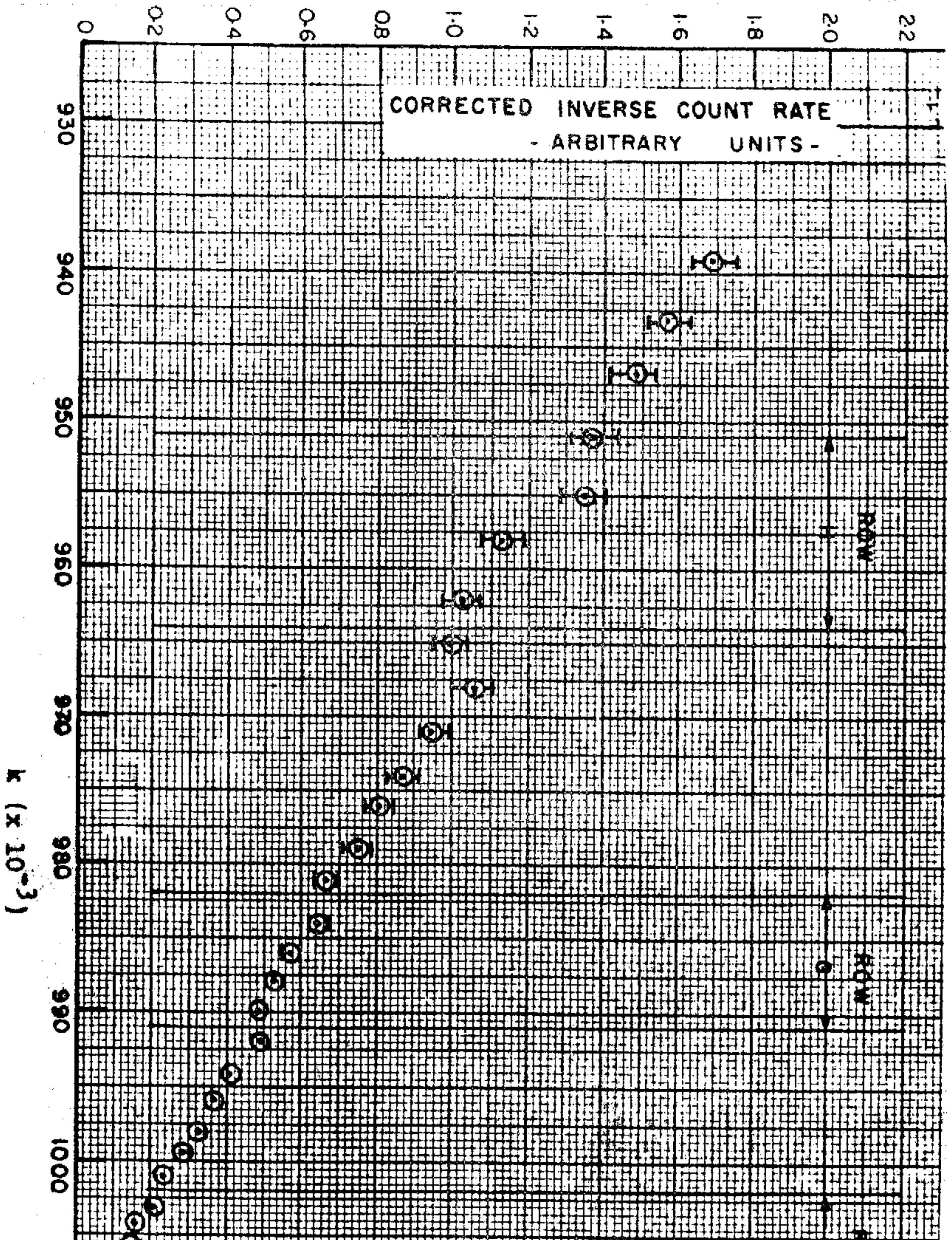
CORRECTED INVERSE COUNT RATE
- ARBITRARY UNITS -
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
930
940
950
960
970
980
990
1000
1010
k (x 10^{-3})
ROW
RCW
ROW

Fig. 4

An alternative approach is to allow the moderator level to rise slowly but steadily initially. An estimate is then made of the increase in moderator height required to double the subcritical power. Half this increase in height should then be required for a further doubling of the power or halving the δk value below critical since:

$$P = \frac{P_s}{\delta k} \text{ numerically}$$

and so when δk is halved, P is doubled. An assessment can then be made by repeating this process, of what the critical level will be. The increase in moderator height required to double the power is rechecked as the level rises until the level is an inch or two below critical. The critical point is then approached cautiously until the power is seen to rise continuously on a long period. The rate log meters should also be indicating the reactor period.

It may not, of course, be considered necessary to go critical on manual control. It is only really necessary to allow the moderator level to rise until the neutron signal is strong enough for automatic regulation. A switch-over is then made from manual to automatic control and the regulating system allowed to bring the reactor to critical.

Changing Reactor Power

Once the reactor is critical, it may be kept at any power level by adjusting the moderator level or control rod positions to keep $k = 1$ or $\delta k = 0$. If the power has to be increased, the moderator level is raised or control rod moved out of the reactor to make k just greater than unity, or δk slightly positive.

Fig. 5, on the following page, shows such a movement in moderator level or control rods at A.

The figure also shows the corresponding changes in k and δk and the resulting exponential increase in power. The reactivity change possible is usually limited by design so that the reactor period during the power increase is long. There is also a reactor trip if this period becomes too small, ie, the rate of increase of power is too high.

At B, the required power level has been reached and the moderator level or control rods are returned to the point where $k = 1$ and $\delta k = 0$. This is somewhat different from the control method in conventional power plants.

In a conventional plant, when an increase in the thermal power is required the firing rate is boosted by opening the fuel

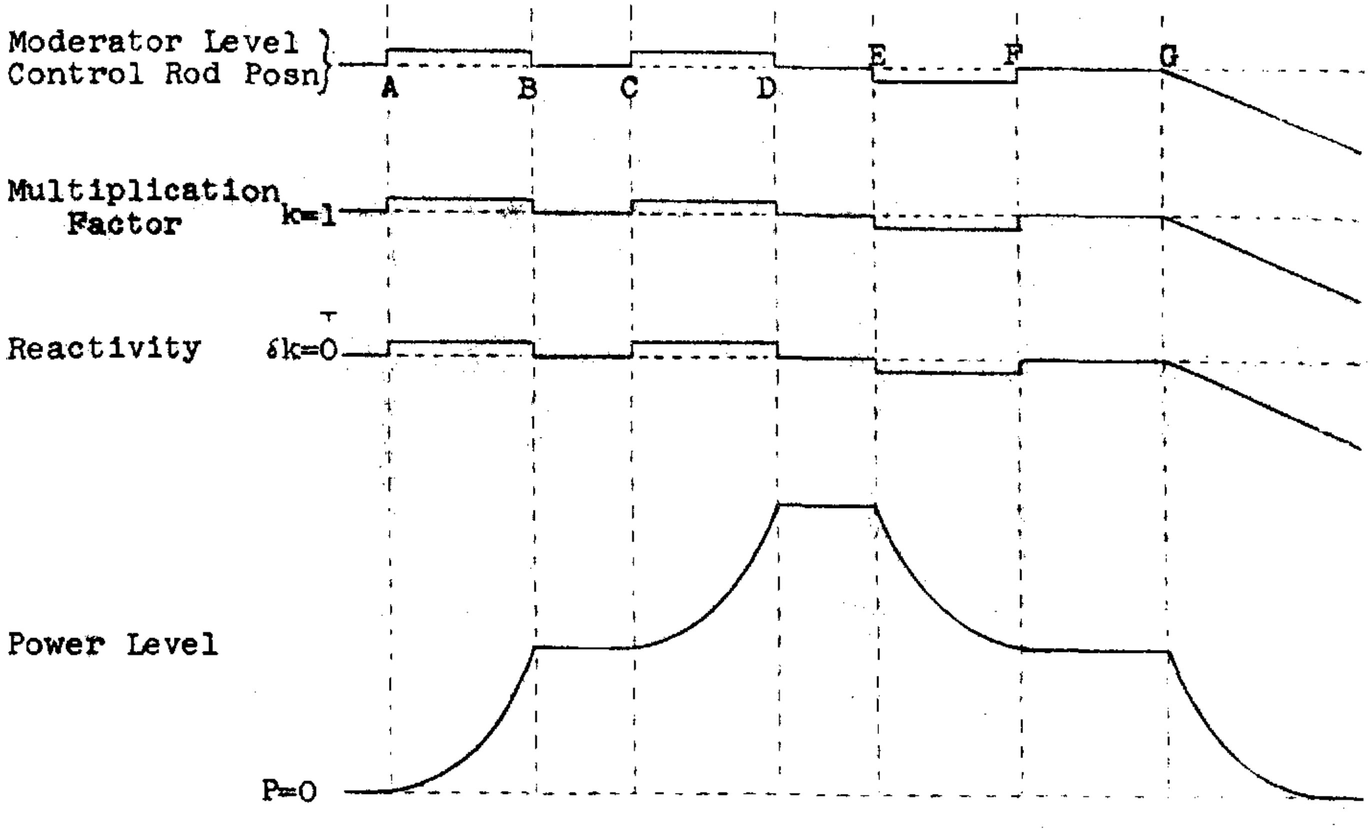

Fig. 5

valve wider and increasing the air flow. The valve is then left open at the new setting. However, in nuclear plants, the moderator level is only raised or the control rods moved while the power is being raised by increasing neutron density. When the correct power level is reached, the moderator or control rods are returned to the old level to prevent further increase in neutron density.

If the power remained steady from D onwards, there would be a gradual rise in moderator level or a gradual movement of control rods out of the core to compensate for fuel burnup or poison buildup, so as to keep $k = 1$ or $\delta k = 0$.

At E the moderator level is lowered or the control rods moved further into the core to lower k slightly below unity. This causes the reactor power to decrease exponentially until the desired lower power level is reached at F. The moderator level or control rod positions are then adjusted so that the reactor is again just critical. At G is shown the beginning of a reactor shutdown controlled by the regulating system. The reactivity decreases slowly and the reduction in neutron power is not rapid compared to the corresponding changes following a trip.

ASSIGNMENT

1. In what condition or state is a reactor in its most dangerous state and why?

2. In terms of subcritical reactor operation, why is it necessary to place a neutron source in the reactor core during the first approach to critical?

3. (a) Give the reasons why the first approach to critical is more hazardous than subsequent approaches to critical with D_2O moderated reactors.

   (b) What additional instrumentation would be required for the initial approach to critical and why?

4. (a) How is the critical moderator level predicted from the count rate?

   (b) How is it known when the reactor is critical?

   (c) The following count rates were recorded, at the moderator depth indicated, during a first approach to critical with a cylindrical reactor, the axis of which is horizontal. Using the graph in Fig. 3 of the lesson to obtain values of the buckling, determine the critical height of moderator. The depth of D_2O at the centre line is 224 cm.

Depth of D_2O (cm)	53	77	117	150	178	203	216	228	238
Count Rate (cpm)	55.5	59.2	68	84	101	141	185	333	606

   (d) What alternative approach is adopted to predict the critical level if the buckling for the reactor in (c) is too difficult to calculate?

5. (a) In a D_2O moderated reactor, why are fission counters not required during subsequent approaches to critical?

   (b) Why is it still necessary to make the initial part of the approach to critical on manual control?

   (c) Briefly describe the two alternative methods that can be used for the approach to critical on manual control and the methods of predicting the critical level in each case.

   (d) Why might it not be necessary to go all the way to critical on manual control and what would be the alternative procedure?

A. Williams